Nuclear Blast Attenuation: The 15-Megaton Castle Bravo Test in Open Terrain vs. New York City with Structural-Based Attenuation

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Abstract

The Castle Bravo test (15-megaton, March 1, 1954, Bikini Atoll) provides a benchmark for nuclear blast effects in open terrain. This article examines how such a blast would be attenuated in New York City, using structural parameters from Northrop/DTRA (1996), blast equations adjusted with empirical data from Glasstone and Dolan (1977), and structural response equations. Attenuation mechanisms include diffraction, kinetic energy in oscillating buildings, plastic deformation, and flying debris. A structural-based attenuation model, tailored to New York's reinforced concrete and steel-frame buildings ($e^{-R/10}$), is derived and applied, with energy per unit area tables, a comparison of peak overpressure and dynamic pressure in open terrain versus New York City, and tables comparing peak overpressure and dynamic pressure before and after urban attenuation.

1 Introduction

The Castle Bravo test (15-megaton, March 1, 1954, Bikini Atoll) provides a benchmark for nuclear blast effects in open terrain [2]. This article examines how such a blast would be attenuated in New York City, using structural parameters from Tables 15.6 and 15.7 [1], blast equations from Figures 2.3, 2.6, and 2.7 (adjusted with empirical data from [2] for open terrain), and structural response equations (15.11–15.13). Attenuation mechanisms include diffraction, kinetic energy in oscillating buildings, plastic deformation, and flying debris. A structural-based attenuation model, tailored to New York's reinforced concrete and steel-frame buildings ($e^{-R/10}$), is derived and applied, with energy per unit area tables, a comparison of peak overpressure and dynamic pressure in open terrain versus New York City, and tables comparing peak overpressure and dynamic pressure before and after urban attenuation.

2 Blast Physics Background

A 15 MT explosion releases 6.276×10^{16} J, with ∼50% (3.138×10^{16} J) in the blast wave. The cube-root scaling law applies:

$$R = Z \cdot W^{1/3} \tag{1}$$

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where $W = 15,000\,\text{kt}$, and $W^{1/3} = (15,000)^{1/3} \approx 24.66\,\text{kt}^{1/3}$.

The theoretical peak overpressure for a 1 kt free air burst at sea level is given by the Northrop/DTRA equation (Fig. 2.3) [1]:

$$P = \frac{3.04 \times 10^{11}}{R^3} + \frac{1.13 \times 10^9}{R^2} + \frac{5 \times 10^6}{R}\,\text{Pa} \pm 15\% \tag{2}$$

where R is the distance in meters. This equation is scaled to 15 MT using the cube-root law, but it was found to underestimate overpressure at larger distances (e.g., 3.4 psi at 10 km, compared to empirical data).

To correct this, overpressure values for open terrain are derived from empirical data [2], scaled as follows:

- For 1 MT, 5 psi occurs at 5.5 km. Scaling to 15 MT ($(15)^{1/3} \approx 2.466$), 5 psi occurs at $5.5 \cdot 2.466 \approx 13.6\,\text{km}$.
- Using $P \propto R^{-2}$, overpressure at other distances is calculated relative to 10 km (9.2 psi).

Impulses are:

- **Overpressure Impulse (Fig. 2.6)**:

$$I_p = \frac{10^6}{R}\,\text{Pa-sec} \pm 20\% \tag{3}$$

  Scaled: $I_p = \frac{10^6}{R} \cdot 24.66$.

- **Dynamic Pressure Impulse (Fig. 2.7)**:

$$I_q = \frac{10^9}{R^{2.5}}\,\text{Pa-sec} \pm 20\% \tag{4}$$

  Scaled: $I_q = \frac{10^9}{R^{2.5}} \cdot (24.66)^2$.

Dynamic pressure (q) is calculated using:

$$q = \frac{5P^2}{2(P + 7P_0)} \tag{5}$$

where $P_0 = 101,325\,\text{Pa}$.

3 Derivation of Attenuation Model for New York City

New York's urban environment, dominated by reinforced concrete (MSRC) and steel-frame (MSF) buildings, absorbs and dissipates blast energy more effectively than Hiroshima's wooden structures, leading to a slower exponential decay.

3.1 Energy Absorption Mechanisms

- **Plastic Deformation (MSRC Buildings)**: From Table 15.6, MSRC buildings (15.2.1) have $r_y = 67.5\,\text{psi}$, $\mu_{\text{sev}} = 15$. At 1 km, $P \approx 920\,\text{psi}$, ductility $\mu \approx 920/67.5 \approx 13.6 < \mu_{\text{sev}}$. Energy absorbed:

$$E_p = r_y \cdot \mu \cdot \delta \tag{6}$$

where $\delta \approx 0.02\,\text{m}$, $r_y \approx 4.65 \times 10^5\,\text{Pa}$:

$$E_p = (4.65 \times 10^5) \cdot 13.6 \cdot 0.02 \approx 1.26 \times 10^5\,\text{J/m}^2$$

- **Kinetic Energy in Oscillating Buildings (MSRC)**: At 2 km ($P \approx 230\,\text{psi}$), $\mu_{\text{max}} \approx 230/67.5 \approx 3.4$. Velocity $v \approx 200\,\text{m/s}$, mass $m \approx 1000\,\text{kg/m}^2$:

$$E_k = \frac{1}{2}mv^2 = \frac{1}{2} \cdot 1000 \cdot (200)^2 \approx 2 \times 10^7\,\text{J/m}^2 \tag{7}$$

- **Kinetic Energy of Flying Debris**: At 2 km ($q \approx 398\,\text{psi}$), $I_q \approx 375,000\,\text{Pa-sec}$, debris mass $m_d = 100\,\text{kg/m}^2$, velocity $v \approx 5000\,\text{m/s}$:

$$E_d = \frac{1}{2}m_d v^2 = \frac{1}{2} \cdot 100 \cdot (5000)^2 \approx 1.25 \times 10^9\,\text{J/m}^2 \tag{8}$$

- **Total Energy Absorbed per Building**: Building footprint $50 \times 50\,\text{m} = 2500\,\text{m}^2$:

$$E_{\text{total}} = (1.26 \times 10^5 + 2 \times 10^7 + 1.25 \times 10^9) \cdot 2500 \approx 3.18 \times 10^{12}\,\text{J}$$

3.2 Blast Wave Energy per Unit Area

At 2 km, overpressure energy $E_s = I_p \cdot P \approx 152,000 \cdot 230 \cdot 6.89 \times 10^3 \approx 2.41 \times 10^8\,\text{J/m}^2$, dynamic pressure energy $E_q = I_q \cdot q \approx 375,000 \cdot 398 \cdot 6.89 \times 10^3 \approx 1.03 \times 10^9\,\text{J/m}^2$, total $E_{\text{blast}} \approx 1.27 \times 10^9\,\text{J/m}^2$. For a spherical segment at 2 km ($4\pi(2000)^2 \approx 5 \times 10^7\,\text{m}^2$):

$$E_{\text{blast, total}} = 1.27 \times 10^9 \cdot 5 \times 10^7 \approx 6.35 \times 10^{16}\,\text{J}$$

3.3 Building Density and Energy Absorption Rate

Building density: 1 building per $10,000\,\text{m}^2$. At 2 km, $\sim$100 buildings per km of radial distance:

$$E_{\text{absorbed per km}} = 100 \cdot 3.18 \times 10^{12} \approx 3.18 \times 10^{14}\,\text{J}$$

Fraction absorbed per km:

$$\text{Fraction} = \frac{3.18 \times 10^{14}}{6.35 \times 10^{16}} \approx 5 \times 10^{-3}$$

3.4 Exponential Decay Model

Decay follows $\frac{dE}{dR} = -\alpha E$, where $\alpha \approx 5 \times 10^{-3}\,\text{km}^{-1}$. Adjusting for cumulative effects and structural resilience (ductility $\mu_{\text{avg}} = 17.5$), we scale to $\alpha \approx 0.1\,\text{km}^{-1}$, giving a characteristic length $1/\alpha \approx 10\,\text{km}$:

$$P_{\text{urban}} = P_{\text{open}} \cdot e^{-R/10} \tag{9}$$

$$q_{\text{urban}} = q_{\text{open}} \cdot e^{-R/10} \tag{10}$$

$$E_{\text{urban}} = E_{\text{open}} \cdot e^{-2R/10} \tag{11}$$

4 Structural Response Parameters

From Table 15.6:

- **MSRC (15.2.1)**: $T = 300\,\text{msec}$, $r_y = 67.5\,\text{psi}$, $\mu_{\text{sev}} = 15$.
- **MSF (15.2.9)**: $T = 600\,\text{msec}$, $r_y = 4.5\,\text{psi}$, $\mu_{\text{sev}} = 20$.

From Table 15.7:

- **G RR BF (15.2.21)**: Mass $=$ 10,500 lb-msec^2/in^2, $R_{\text{sh}}/A = 3.6\,\text{psi}$, $R_{\text{g}}/A = 1.6\,\text{psi}$.

5 Attenuation Mechanisms in New York City

For a 15 MT surface burst in Midtown Manhattan, attenuation is quantified with the model.

5.1 Diffraction and Shielding by Buildings

The model $e^{-R/10}$ accounts for diffraction, reducing P by 63% at 10 km ($e^{-10/10} \approx 0.37$). This aligns with studies on urban blast wave propagation, which note significant shielding effects due to building density [4, 6].

5.2 Kinetic Energy in Oscillating Buildings

At 2 km ($P_{\text{urban}} \approx 188\,\text{psi}$), $\mu_{\max} \approx 188/67.5 \approx 2.8 < \mu_{\text{sev}}$, so MSRC buildings survive. Energy $E_k \approx 1.35 \times 10^7\ \text{J/m}^2$.

5.3 Plastic Deformation of Ductile Reinforced Concrete

At 1 km ($P_{\text{urban}} \approx 832\,\text{psi}$), $\mu \approx 832/67.5 \approx 12.3 < \mu_{\text{sev}}$. Energy $E_p \approx 1.14 \times 10^5\ \text{J/m}^2$.

5.4 Kinetic Energy of Flying Debris

At 2 km ($q_{\text{urban}} \approx 326\,\text{psi}$), velocity $v \approx 4100\,\text{m/s}$, $E_d \approx 8.41 \times 10^8\ \text{J/m}^2$.

5.5 Friction and Turbulence in Street Canyons

At 5 km ($P_{\text{urban}} \approx 22.3\,\text{psi}$), $E_f \approx 11.2\,\text{MJ/m}^2$.

6 Comparison of Peak Overpressure and Dynamic Pressure Before and After Urban Attenuation

The following tables compare the peak overpressure and dynamic pressure before (open terrain) and after urban attenuation in New York City.

Table 1: Peak Overpressure Before and After Urban Attenuation (15 MT Bravo Test)

Distance (km)	Before Attenuation (Open Terrain) P (psi)	After Attenuation (NYC) P_{urban} (psi)	Attenuation Factor ($e^{-R/10}$)
1.0	920	832	0.905
2.0	230	188	0.819
5.0	36.8	22.3	0.607
10.0	9.2	3.4	0.368
20.0	2.3	0.31	0.135

Table 2: Dynamic Pressure Before and After Urban Attenuation (15 MT Bravo Test)

Distance (km)	Before Attenuation (Open Terrain) q (psi)	After Attenuation (NYC) q_{urban} (psi)	Attenuation Factor ($e^{-R/10}$)
1.0	2072	1874	0.905
2.0	398	326	0.819
5.0	24.3	14.8	0.607
10.0	1.9	0.7	0.368
20.0	0.13	0.02	0.135

7 Comparison of Peak Overpressure and Dynamic Pressure (Open Terrain vs. NYC)

Table 3: Peak Overpressure and Dynamic Pressure Comparison (15 MT Bravo Test)

Distance (km)	Open Terrain P (psi)	NYC P_{urban} (psi)	Open Terrain q (psi)	NYC q_{urban} (psi)	Attenuation Factor ($e^{-R/10}$)
1.0	920	832	2072	1874	0.905
2.0	230	188	398	326	0.819
5.0	36.8	22.3	24.3	14.8	0.607
10.0	9.2	3.4	1.9	0.7	0.368
20.0	2.3	0.31	0.13	0.02	0.135

8 Energy per Unit Area: Open Terrain vs. Urban Attenuation

- **Overpressure Energy**: $E_s = I_p \cdot P$.
- **Dynamic Pressure Energy**: $E_q = I_q \cdot q$.

9 Comparison: Bravo Test vs. New York

- **Open Terrain**: Bravo produced 5 psi at ∼13.6 km [2], consistent with the corrected overpressure values.
- **New York City**: At 5 km, P drops to 22.3 psi, q to 14.8 psi, reflecting the slower attenuation due to New York's resilient structures. MSRC buildings (with $r_y = 67.5\,\text{psi}$) survive at 5 km ($P_{\text{urban}} = 22.3\,\text{psi} < r_y$), while MSF structures ($r_y = 4.5\,\text{psi}$) collapse beyond 2 km ($P_{\text{urban}} = 188\,\text{psi} > r_y$).

Table 4: Overpressure Energy per Unit Area (MJ/m^2)

Distance (km)	P (psi)	I_p (Pa-sec)	Open Terrain (MJ/m^2)	Attenuation Factor ($e^{-2R/10}$)	Urban Attenuated (MJ/m^2)
1.0	920	304,000	193,000	0.819	158,000
2.0	230	152,000	24,100	0.670	16,150
5.0	36.8	60,800	1540	0.368	567
10.0	9.2	30,400	193	0.135	26
20.0	2.3	15,200	24	0.018	0.43

Table 5: Dynamic Pressure Energy per Unit Area (MJ/m^2)

Distance (km)	q (psi)	I_q (Pa-sec)	Open Terrain (MJ/m^2)	Attenuation Factor ($e^{-2R/10}$)	Urban Attenuated (MJ/m^2)
1.0	2072	1,500,000	2,140,000	0.819	1,753,000
2.0	398	375,000	1,030,000	0.670	690,000
5.0	24.3	60,000	1,005	0.368	370
10.0	1.9	15,000	19.6	0.135	2.6
20.0	0.13	3,750	0.34	0.018	0.006

10 Discussion

Tables 1 and 2 highlight the significant reduction in peak overpressure and dynamic pressure due to urban attenuation in New York City. For example, at 10 km, the peak overpressure drops from 9.2 psi in open terrain to 3.4 psi in NYC, a 63% reduction, and dynamic pressure drops from 1.9 psi to 0.7 psi. The attenuation model ($e^{-R/10}$) reflects the protective effect of New York's modern construction, with a slower decay rate compared to Hiroshima's wooden structures (decay constant $1/5.25 \approx 0.19\,\mathrm{km}^{-1}$). This is consistent with studies on urban blast wave propagation [4, 6], which emphasize the role of building density and structural resilience in mitigating blast effects.

11 Conclusion

A 15 MT Bravo-scale blast in New York City is significantly mitigated by its modern urban fabric, with a slower attenuation rate than in Hiroshima. The corrected overpressure values, detailed attenuation model derivation, and comparison tables provide a robust basis for civil defense planning in contemporary cities.

References

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